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A STEPPED-FREQUENCY HF RADAR FOR IONOSPHERIC DIAGNOSTICS

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Naturally occurring ionospheric disturbances generate structure over an extremely large range of scale sizes and intensities. To diagnose the interacting plasma processes that cause this structure continuum requires a variety of complex instruments. This report describes a multiple-frequency HF backscatter radar that can measure the Doppler spectrum of structure in the scale-size region from tens of meters to meters. This structure regime is important in its own right and acts as tracer for macroscale parameters such as plasma depletions, currents, and electric fields.

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I INTRODUCTION

Naturally occurring ionospheric disturbances generate irregularities over extremely large ranges of scale sizes and intensities. Understanding the interrelated physical processes that sustain these structures is important for modeling naturally occurring processes and similar processes that may occur in a disturbed nuclear environment. A variety of instrumentation is required to diagnose these processes fully.

The Wideband Satellite [Rino et al., 1980], for example, has made extensive equatorial and auroral-zone scintillation measurements from which irregularity structures down to a few hundred meters can be inferred. Rocket probes have recently made measurements down to one-meter scale sizes. Evidence of significant structures at smaller scale sizes has come exclusiv_ly from measurements made by backscatter radars, which are sensitive to structures characterized by the spatial wave number, k, that is twice the spatial wave number of the radar frequency ($k = 2k_R = 4\pi/\lambda_R = 4\pi f_R/c$).

The enhanced backscatter occurs when plasma waves are excited by a variety of instability mechanisms. Depending on the instability "driver," the backscatter strength and Doppler shift can be used to measure background ionospheric parameters. The Homer [Tsunoda and Presnell, 1976] and STARE [Greenwald et al., 1978] radars have been used to map auroral-zone electric fields spatially. Backscatter at 50 MHz from the equatorial electrojet and the auroral electrojet has been shown, experimentally [Farley, 1970; Greenwald et al., 1973] and theoretically [Sudan and Keskinen, 1979] to be proportional to the strength of the electrojet current. Moreover, the Doppler structure of the backscatter echo is related to the plasma dispersion relation of the instability.

Most of the scientific applications of radar backscatter have been pursued at VHF where refractive bending of the radar ray is negligible. It is recognized, however, that operation at lower HF frequencies can potentially explore larger irregularity structures. Such operation,

however, must accommodate all the complexities introduced by refractive ray bending. Nonetheless, refractive bending can be used advantageously to achieve the necessary perpendicularity condition in regions that would otherwise be inaccessible for radar backscatter measurements.

In this report, therefore, we have emphasized a system that can accommodate essentially the entire HF range. In such a system the highest pulse repetition rate can only be achieved at the higher frequencies where ground clutter is minimized. Operational agility, i.e., a well-designed control system, is the key to the successful operation of such a radar.

A major concern in the design of such a radar is the size and cost of an antenna system that can probe the longest wavelengths of interest. The proposed antenna system consists of two log-periodic antenna arrays to cover the 8- to 64-MHz frequency range. The savings are substantial, however, if the lowest frequencies are eliminated.

Both the transmitter and receiver use conventional hardware available from electronic component manufacturers. The radar-control system employs a programmed microprocessor to set the frequency hopping and transmitter dwell times. The data-acquisition system uses a minicomputer in association with a correlator or array processor to integrate and analyze spectrally the digitally recorded data.

Section II of this report first describes in detail the constraints that dictate the performance requirements for the major system elements. Section II then describes in detail an antenna system, a transmitter, a receiver, and a control and data acquisition system that meet the design criteria. Section III describes the estimated costs of building the radar system and our recommendations for its implementation.

II HF DIAGNOSTIC RADAR

A. General Considerations

Considerable experience has been gained over the last decade in using HF backscatter radars to measure quantitatively the backscatter from highly field-aligned irregularities known to be associated with auroral and equatorial spread F. We describe the design of an HF radar system that fully exploits this technology for monitoring and diagnosing spread F.

The functional elements of the radar include (1) the antenna system, (2) the transmitter, (3) the receiver, and (4) the control and data acquisition system The transmitter and receiver are comparitively straightforward. We propose a coherent pulsed system that can be stepped in frequency from 8 MHz to 64 MHz with at least 20-kW peak power.

The lowest usable frequency is dictated by the ionospheric critical frequency and the severity of refractive effects as well as the size and complexity of the antenna system. The highest frequency is dictated by the achievable sensitivity, because the echo strength falls off very rapidly with increasing frequency. The system can, of course, be also used for HF propagation experiments in their own right.

The control and data acquisition system must control the frequency hopping and transmitter dwell and preprocess and digitally record the data as well as provide real-time displays. Determination of the echo Doppler structure and mean Doppler shift is essential to identify the physical processes associated with the enhanced plasma waves and, at the lowest frequencies, for identifiying refractive effects. Thus, the data acquisition system must include a correlator or fast Fourier transform (FFT) processing capability.

B. Sensitivity

As outlined previously, stepped-frequency HF backscatter radar can directly detect field-aligned backscatter. With sufficient sensitivity and appropriately designed antennas, the radar can quantitatively measure the striation spectral-density function in the small-scale (diffusion) regime and the Doppler spectrum.

As noted above, the critical frequency and refractive effects govern the lowest usable frequency for the backscatter measurements. Sensitivity dictates the highest frequency, because the echo strength falls off very rapidly with increasing frequency. Chesnut [1980] and Woodman and Basu [1978] have postulated that a significant change in the spectral-density function can be expected at $f \approx 30$ MHz; therefore, the radar frequency band should include this frequency range.

Extensive measurements of field-aligned backscatter associated with equatorial spread F have been performed by Balsley et al., [1972] at 55 MHz. We have, therefore, chosen as a baseline the capabilities of the 55-MHz radar system described by Balsley et al. [1972]. If we achieve the necessary sensitivity to detect field-aligned backscatter at 50 MHz, we expect to be able to characterize the striation spectral density in the small-scale regime.

Using a point-target figure of merit defined as

$$F.M. = P_T G^2 \lambda \tau \tag{1}$$

where P_T is the peak power, G is the antenna gain, λ is the wavelength, and τ is the pulse width, the system used by Balsley et al., [1972], had an F.M. = 1.2×10^6 Wms for a pulse length of 100 μs. For a beam filling target, the figure of merit is τ^2 dependent. In addition, the radar sensitivity is affected by duty cycle and dwell time. These quantities are in turn determined by the desired range resolution, expected return-signal Doppler shift, and allowable range ambiguity. The specific constraints are described below.

C. Operational Parameters

To derive the radar operational parameters such as pulse length, pulse repetition frequency, and dwell time at each frequency, we have to examine their interrelationships. For a pulse of duration, τ, the range resolution is given by the formula

$$\Delta R = \frac{c\tau}{2} \qquad (2)$$

Thus, τ is determined by range resolution requirements or, conversely, the achievable range resolution is determined by τ as dictated by sensitivity requirements.

For a pulse-repetition rate of f_r Hz, echoes from beyond

$$R_a = \frac{c}{2f_r} \qquad (3)$$

are superimposed on echoes from the primary ranges of interest and are, therefore, ambiguous. The maximum expected echo range, therefore, sets an upper bound on f_r. The quantity, f_r, also determines the Nyquist frequency, or the maximum unambiguously measurable velocity, because Doppler shifts beyond

$$V_a = \frac{\lambda f_r}{2} \qquad (4)$$

fall within the primary Doppler interval.

To place some limits on the radar operational parameters we need to look at the characteristics of the medium to be measured. The spectral measurements of equatorial spread-F backscatter by Balsley et al. [1972], and Woodman and La Hoz [1976] show that at 50-MHz spectral widths as broad as 100 Hz can be expected. In addition, the return signals can have a Doppler shift of as much as 100 Hz. Backscatter measurements at 150 MHz by Tsunoda [1980] show that return strength falls off rapidly for ranges in excess of ~ 750 km.

The above measurements dictate a maximum usable f_r = 200 Hz, corresponding to R_a = 750 km, and a minimum usable f_r = 100 Hz, corresponding

to a Doppler shift (or spectral width) of 100 Hz. Since available broadband HF transmitters operate with duty cycles of ~ 2%, the pulse repetition rate of 200 to 100 Hz sets the maximum pulse length at 100 to 200 μs. The resulting range resolution is from 15 to 30 km, or better if shorter pulses or compressed pulses are used.

Additional limitations are placed on the radar operational parameters by the presence of single hop ground reflection returns. These clutter returns are both time and frequency dependent. In order to accommodate the clutter returns,the control and data acquisition system will need to be able to adjust the radar operational parameters in real time. The immediate effect of the ground reflection returns is the need to reduce f_r in order to accept a larger R_a. Dwell time will need to be increased to maintain spectral measurement error bars at an acceptable level. It is clear that the requirement to reduce f_r will severely limit the spectral measurement capability of the radar.

Dwell time, $t_o = n/f_r$, where n is the number of pulses, sets velocity resolution by the formula

$$\Delta V = \frac{\lambda}{2t_o} \tag{5}$$

To obtain a velocity resolution of 3 m/s at 50 MHz (corresponding to a one-Hz Doppler resolution) requires a coherent processing time of one second. However, to obtain spectral measurement error bars of less than two percent using the previously determined pulse repetition rates of 100 to 200 Hz, the dwell time would have to be increased to 15 s to allow averaging of the measured spectra.

The maximum observation time is set by the ionospheric motion and the antenna beamwidth transverse to the ionospheric motion. Using 300 m/s as the maximum ionospheric motion velocity and assuming a 5° antenna beamwidth, gives 100 s as the time required for a backscatter feature at an altitude of 300 to 400 km to move through the antenna beam. This limitation will allow seven transmitted frequencies to be used with a dwell time of 15 s at each frequency. The frequency range from 4- to 64-MHz can be adequately covered by seven frequency settings at 8, 12,

16,24,32,48, and 64 MHz. If a narrower beamwidth antenna is used either the dwell time or frequency coverage will have to be reduced.

The proposed stepped-frequency HF radar should have the following performance:

- Pulse repetition frequency, $f_r \leq 200$ Hz
- Pulse length, $\Delta t_p \geq 100$ μs
- Dwell time, $t_o \leq 15$ s
- Operating frequencies, $f \approx 8$, 12, 16, 24, 32, 48, and 64 MHz

These parameters are consistent with available two percent duty cycle transmitters and will accommodate ionospheric velocities of up to 300 m/s.

D. Antenna

1. Overall Requirements

The proposed stepped-frequency HF radar frequency range extends from 8 to 64 MHz. To measure the characteristics of the striation spectral-density function in the small-scale regime as a function of wavelength, the radar has to operate at several frequencies, and the change from one operational frequency to another has to be rapid, i.e., it has to occur well within one interpulse period. Thus the antenna must be broadband or we need several antennas (one for each frequency used) with a rapid-switching capability from one to another.

To achieve adequate sensitivity for the proposed measurements the antenna gain at 50 MHz (our baseline point) needs to be ≥ 20 dB. At lower frequencies the gain can be lower and at higher frequencies it will need to be higher. Moreover, to limit the extent of the ionosphere from which the backscatter is measured, the antenna beamwidth has to be narrow in the east-west direction (the north-south direction is automatically limited by the aspect sensitivity imposed by the highly field-aligned irregularities).

To map the backscatter strength spatially, the antenna would scan in the east-west direction. This, however, would only be done at a single frequency; one high enough that the antenna size will permit economical physical movement.

Some physical requirements arise from the required antenna electrical properties. Because this HF radar system is not likely to be a permanent installation, it should be transportable. It should also be compact enough to be used where only very limited land is available, e.g., Roi Namur Island.

2. Design Choices

The most common antenna type for HF radars is an array of dipoles. To achieve the necessary gain approximately 100 elements will have to be installed at each frequency used. If the arrays were square (i.e., 10 x 10) or rectangular (i.e., 4 x 25) with 0.5-λ element spacing the area required for the highest frequency (64 MHz) would be $\approx$ 550 m^2 ($\approx$ 0.14 acre) and for the lowest frequency (8 MHz) $\approx$ 35,000 m^2 ($\approx$ 8.5 acres). The limited land available for most temporary operations generally precludes the possibility of constructing large multiple arrays. Placing the arrays over water, such as on the lagoon side of Roi Namur Island is complicated not only by construction and maintenance problems but also by the varying height of the ground plane as the ocean surface changes.

Broadband antennas, therefore, are the most attractive solution for a viable antenna design. A common broadband antenna type is the log-periodic. HF communication systems have routinely used this kind of antenna. Single, commercially available, log-periodic antennas can provide 7- to 16-dBi gain with 40° to 60° beamwidths. Figure 1 shows an example of an antenna pattern of an inverted log-periodic mounted between two support towers. The sample pattern shown is for the lowest frequency of a horizontally polarized inverted log-periodic antenna. As frequency increases the H-plane pattern broadens and develops two lobes. This effect, however, is not prevlaent until the frequency is tripled.

Using the log-periodic antenna as an element in a linear array can give the desired gain of $\geq$ 20 dB as well as provide a vertical fan-shaped beam. The half-power beamwidth (in degrees) is given by

$$\theta \simeq \frac{50\lambda}{L} \qquad (6)$$

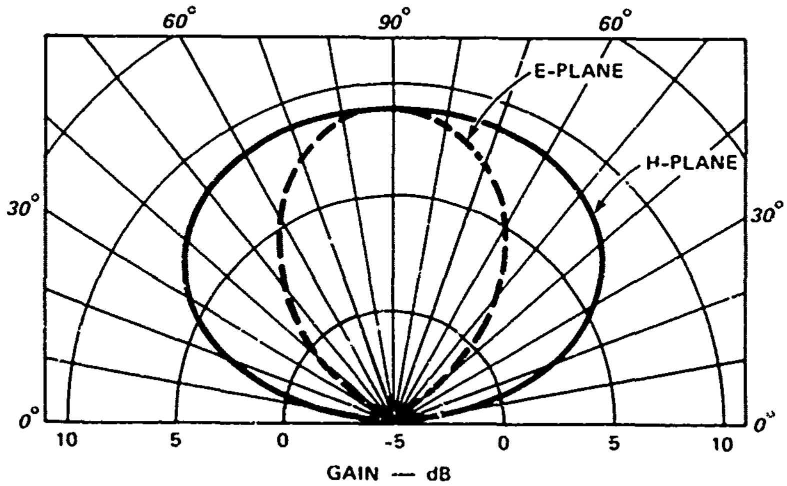

FIGURE 1 PATTERN OF AN INVERTED LOG-PERIODIC ANTENNA

where L is the length of the linear array. The effect of element spacing on array gain is shown in Figure 2. Thus, if the HF radar frequency coverage is broken into the 64- to 24-MHz band and 24- to 8-MHz band, the element spacing can be made 0.9 λ at the top of the band (if 8 or more elements were used) and 0.36 λ at the bottom of the band. The approximate 3.5-dB difference in array gain across the band will easily be made up by the increasing echo strength with decreasing frequency.

Splitting the HF radar frequency coverage into two bands offers another advantage. Namely, construction can be done in stages. If the higher-frequency band, which requires the least amount of land, provides sufficient data to characterize the striation spectral-density function in the small-scale regime, then the lower-frequency band may be eliminated. The required gain of $\geq$ 20 dB can be attained with 12 elements in a linear array. If the lower frequency band needed to be built, eight elements would auffice. The resulting beam will be fan shaped with a 5° by 40 to 60° beamwidth.

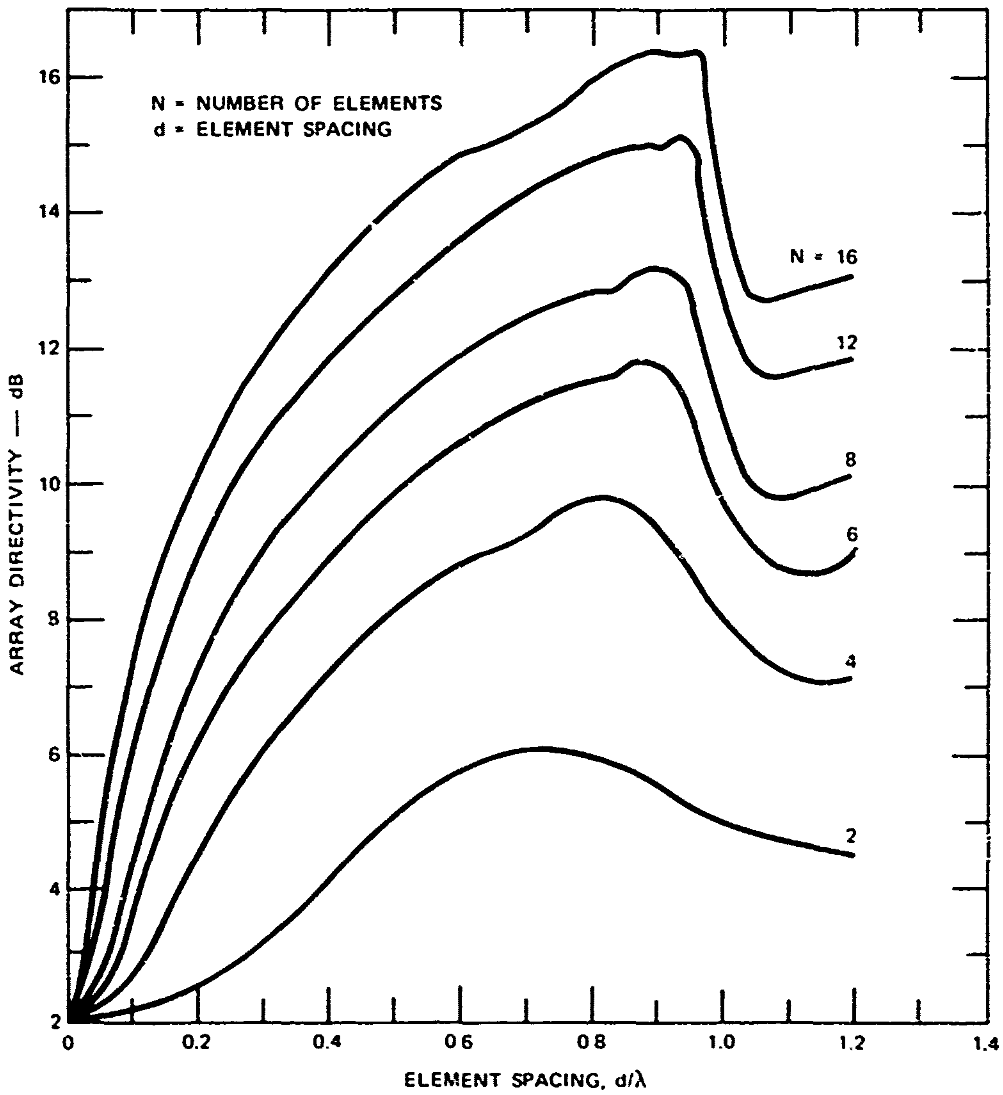

FIGURE 2 ARRAY DIRECTIVITY VERSUS ELEMENT SPACING

3. Scanning Option

An electronic scanning capability for the HF radar can be used to map the field-aligned backscatter strength spatially. Such mapping has been previously done by using the mechanically steerable ALTAIR radar on Roi Namur Island [Tsunoda et al., 1979].

Although we have not costed the scanning option, the possibility of scanning at one frequency is considered in the following discussion. For the simple case of an equally spaced linear array, a main beam that is θ^{o} off the array normal is formed by successively applying a phase difference of $\Delta\phi$ rad to each of the array elements:

$$\Delta\phi = \frac{2\pi}{\lambda} d \sin \theta \tag{7}$$

where d is the spacing between elements. Thus, the actual phase shift, ϕ_m, applied to the m^{th} element is a row of m equally spaced elements is:

$$\phi_m = (m - 1) \Delta\phi - g_m \tag{8}$$

where g_m is the phase-shift correction resulting from the transmission path to the m^{th} element.

Because the proposed array elements are log-periodic antennas with 40^{o} to 60^{o} beamwidth, the scan capability will be limited from $\pm 20^{o}$ to $\pm 30^{o}$ off the array normal. Furthermore, with an array beamwidth of $\sim 5^{o}$ eight to twelve independent positions can be realized. The complexity of maintaining the appropriate phase relationships is, however, a severe constraint.

E. Transmitter and Receiver

1. Overall Requirements

The broadband characteristics of the proposed radar are the controlling requirements of both the transmitter and receiver. The system sensitivity needs place minimum peak power requirements on the transmitter. Moreover, to switch from one operating frequency to another rapidly, the transmitter needs to be driven by an agile frequency source.

The measured quantities will deal with both the returned signal strength and spectral characteristics. Because the returned signal strength is expected to vary significantly across the proposed radar frequency band, the receiver needs to have a high dynamic range. To make the spectral measurements, the transmitter/receiver must also maintain frequency coherence. These requirements are readily achieved in commercially available equipment.

2. Design and Suppliers

To satisfy both the transmitter frequency agility and system coherence requirements, a central element in the design is the frequency synthesizer. The desired peak power of $\geq$ 20 kW at a two-percent duty cycle over the desired frequency range can be attained with hardware supplied by commercial contractors. Transmitter designs that cover the 8- to 64-MHz band have been previously used by Granger Associates in HF sounders and by Applied Research Corporation in over-the-horizon (OTH) systems.

A block diagram of the proposed HF radar transmit section is shown in Figure 3. Agility in transmitting frequency is provided by a frequency synthesizer that drives the high-power transmitter. The basic block diagram of a suitable receiver section is shown in Figure 4. The receiver consists of commercially available preamplifiers, filters, mixers, attenuators, power splitters, and miscellaneous other parts. To maintain frequency coherence, the same common local oscillator is used both in the transmit and receive sections of the radar.

The actual implementation of the low-power level part of the transmitter and the whole receiver can be accomplished by using a commercially available receiver such as the RACAL RA 6790. The addition of mixer, amplifier, and filter components gives the receiver a frequency generating capability; thus, it can also be used to drive the transmitter. The RA 6790 covers the frequency range from 0.5 to 30 MHz, therefore, a conversion stage will be added to extend its capabilities to 60 MHz.

F. Control and Data Acquisition

1. Overall Requirements

The three principal parts of system control and data processing are the control of operating parameters of the radar; acquisition, preprocessing, and recording of the radar data; and display in real-time of the experiment status.

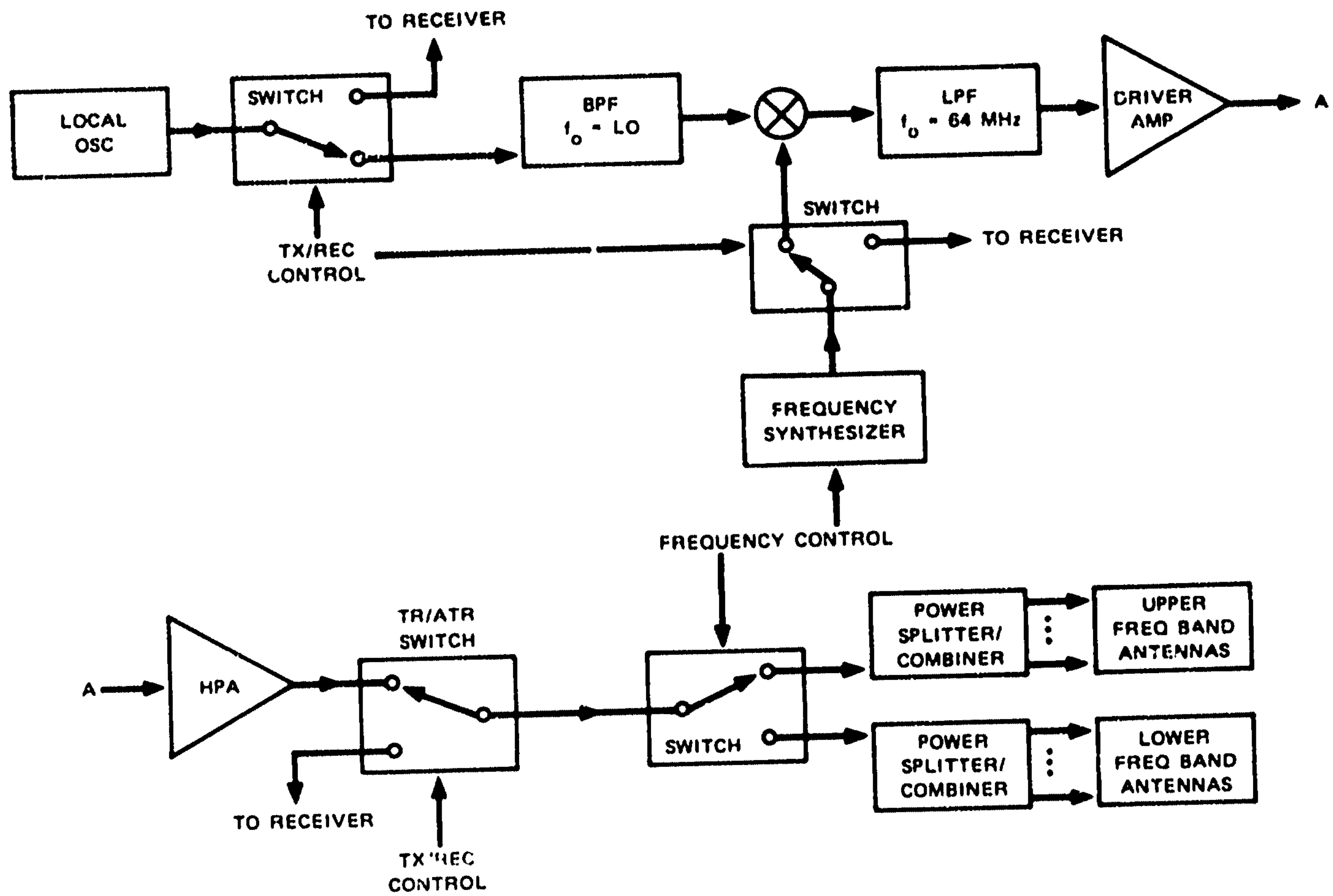

FIGURE 3 TRANSMIT SECTION BLOCK DIAGRAM

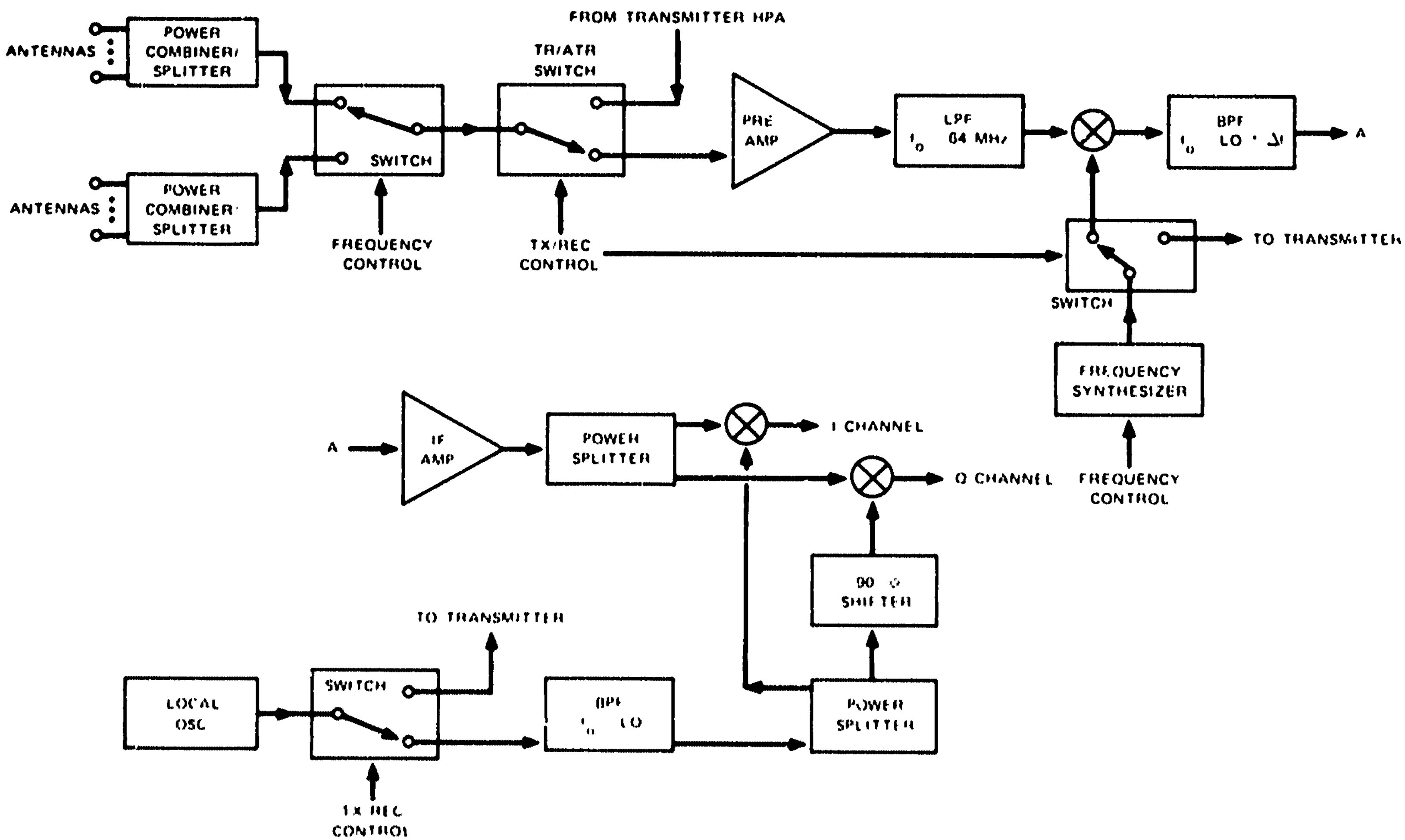

FIGURE 4 RECEIVE SECTION BLOCK DIAGRAM

The control system needs to select:

- Transmit frequency and dwell time
- Transmit antenna (if more than one is used)
- Transmit/receive switch state
- Local oscillator control to transmit/receive sections
- Receiver attenuation level
- Phasing for antenna scanning (if implemented)
- Data sampling commands.

The data acquisition preprocessing and recording system needs to:

- Convert the analog signal to digital data
- Integrate the digital data
- Perform spectral preprocessing
- Record the integrated and preprocessed data
- Record radar system parameter status

The display system needs to:

- Provide display of system operating parameters
- Display real-time returned signal parameters.

2. Design

A block diagram of the proposed system control and data processing elements of the radar are shown in Figure 5. The microprocessor system control unit will send the various control signals. The control unit is driven by a minicomputer. The minicomputer will be programmed to acquire the sampled data, integrate and preprocess the digital data, record the data and system operating parameters, and control the display units. The desired system operation parameters can be entered or changed in the minicomputer via a cassette recorder or a CRT/terminal. SRI International has designed several systems of this type for similar systems.

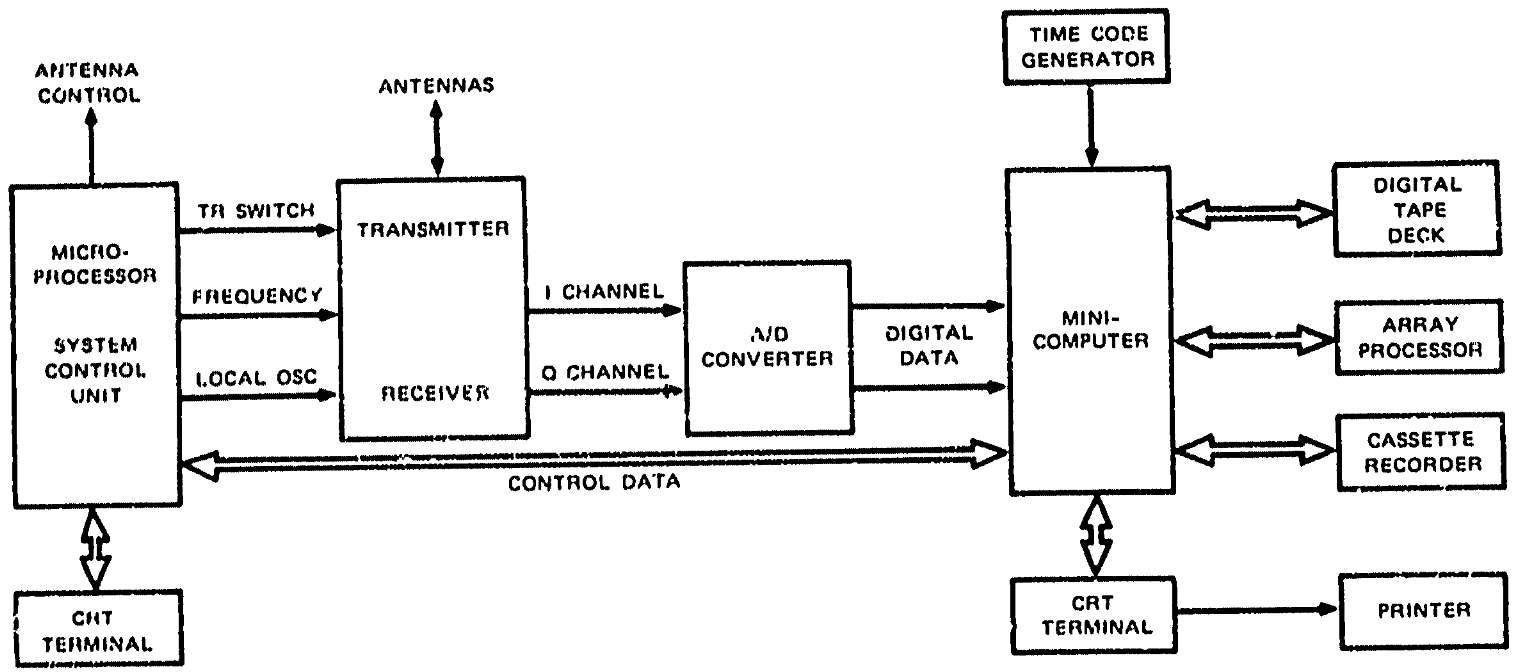

FIGURE 5 SYSTEM CONTROL AND DATA PROCESSING BLOCK DIAGRAM

III SYSTEM COSTS AND RECOMMENDATIONS

We have made a preliminary cost estimate of constructing an operational stepped-frequency radar with the capabilities described in Section II. The cost estimates presented are guidelines based on vendor quotes. Whenever possible, however, Defense Nuclear Agency (DNA) facility equipment presently at SRI International has been included to minimize costs. For example, the Granger Associates HF sounder transmitter, which was used during the LAGOPEDO experiment, can be refurbished for approximately $20,000, whereas a new Applied Research Corporation HF transmitter will cost approximately $100,000. We also assume that the Wideband HP 2100 computer systems will be used.

As discussed in Section II.D.2, the HF radar frequency coverage can be advantageously split into two bands: one operating from 24 to 64 MHz and the other from 8 to 24 MHz. The estimated costs of the lower and upper frequency portion antennas are $75,000 and $25,000, respectively. We have also estimated the cost of a single log-periodic antenna covering a 2:1 frequency range starting at 32 MHz that can be mechanically steered for broad-area coverage. The estimated hardware costs for the three systems are summarized in Table 1. Costs for the scanning option have not been included in these figures.

In addition to the hardware, approximately eight man-months of labor will be required to assemble, interface, and test the rf components. In addition, approximately eighteen man-months of labor will be required to assemble and test the control, data acquisition, and real-time display system. The manpower costs are summarized in Table 2. The actual costs are based on senior professional and technical/programmer projected hourly rates for 1982.

The initial motivation for developing the stepped-frequency radar was to measure quantitatively the equatorial spread F spectrum through the scale-size regime encompassing the ion gyroradius (~ 6 m) where both

Table 1

HARDWARE COSTS

	Frequency Range		
	08 to 64 MHz	24 to 64 MHz	32 to 64 MHz*
Antenna system	$100,000	$25,000	$25,000+ $10,000‡
Transmitter	5,000	5,000	5,000
Receiver	10,000	10,000	10,000
Data acquisition and control	50,000	50,000	50,000
Total	$165,000	$90,000	$90,000

Table 2

LABOR COSTS

	Frequency Range		
	08 to 64 MHz	24 to 64 MHz	32 to 64 MHz*
Antenna system	$15,000	$ $10,000	$5,000
Transmitter	20,000	20,000	20,000
Receiver	25,000	25,000	20,000
Data acquisition and control	150,000	125,000	100,000
Total	$210,000	$180,000	$145,000

*Single log-periodic rotatable antenna.

+Electrically rotated.

‡Mechanically rotated.

theory and indirect experimental data suggest a rapid possibly Gaussian decrease in spectral intensity with increasing spatial frequency. Data from the PLUMEX experiment as well as theoretical work to understand the "freezing phenomenon" have shown that spectral steepening begins at much larger wavelengths, perhaps as large as 200 m.

Because there wavelengths are inaccessible to backscatter measurements, the originrl objectives of the experiment even if fully met will not answer some new questions that have arisen. On the other hand, the broader capabilities of the system discussed in Section I underscore the fact that the capabilities of a stepped-frequency HF backscatter radar with a Doppler processing capability go well beyond the quantitative measurement of the backscatter spatial wavelength spectrum, which is the most difficult measurement to make.

With this in mind, therefore, we have roughly estimated the costs of locating and operating the radar on Roi Namur Island and at a Polar Cap station such as Resolute Bay. The costs are summarized in Table 3. The installation and operating costs are clearly higher for Polar Cap operations. On the other hand, a simple mechanically steerable antenna is adequate for the broad-area surveillance applications of primary interest in the polar cap.

The hardware, labor, and installation costs for placement of the radar either in the arctic or near the equator are summarized in Table 4. Thus, for roughly comparable overall system costs, the basic HF radar system with a limited frequency range can be fielded for operations at the equator or in the polar cap. Moreover, the system capabilities can be expanded as necessary, e.g., completely automated operation may ultimately be desired.

In summary, the stepped-frequency HF radar described in this report is an important diagnostic tool that can serve a variety of data gathering needs that will develop as theoretical refinements and the DNA auroral and polar-cap programs evolve. In short, the costs of the system are justified by the expected results that it will likely generate.

Table 3

INSTALLATION AND OPERATION COSTS

(a) Equatorial Installation

	Frequency		
	08 to 64 MHz	24 to 64 MHz	32 to 64 MHz
Labor	$50,000	$30,000	$25,000
Direct Costs	25,000	20,000	20,000
Total	$75,000	$50,000	$45,000

(b) Arctic Installation

	Frequency		
	08 to 64 MHz	24 to 64 MHz	32 to 64 MHz
Labor	$150,000	$90,000	$75,000
Direct Costs	50,000	40,000	40,000
Total	$200,000	$130,000	$115,000

(c) Operation Costs - Weekly

Labor & Direct Costs	Frequency		
	08 to 64 MHz	24 to 64 MHz	32 to 64 MHz
Equatorial	$5,000	$5,000	$5,000
Arctic	$6,000	$6,000	$6,000

Table 4

COST SUMMARY

(a) Equatorial

	Frequency		
	08 to 64 MHz	24 to 64 MHz	32 to 64 MHz
Hardware	$165,000	$90,000	$90,000
Labor	$210,000	$180,000	$145,000
Installation	$75,000	$50,000	$45,000
Total	$450,000	$320,000	$280,000

(b) Arctic

	Frequency		
	08 to 64 MHz	24 to 64 MHz	32 to 64 MHz
Hardware	$165,000	$90,000	$90,000
Labor	$210,000	$180,000	$145,000
Installation	$200,000	$130,000	$115,000
Total	$575,000	$400,000	$350,000

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